Lego Robotics Invention System

Part 2: working with sensors

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In the first part of this series of articles, we looked at the philosophy behind the Lego Robotics Invention System, the features of the system and the power of the RCX block. In this second part, we give our attention to the manner in which the RCX block works with sensors, which are the eyes and ears of a robot. In addition, we reveal how you can build your own sensors.

The RCX block, which is the key component of the Robotics Invention System, contains a complete microcontroller system. Up to three sensors can be connected to this block. These sensors enable the robot, to perceive 'sensations' from its environment. There are several types of ready-made sensors, including switches, reflective sensors, temperature pickups, rotation pickups and so on. Although the range of available sensors is fairly complete, Elektor readers will surely see the RCX interface as a challenge to develop their own, new sensors. As you will see, this is also possible. In addition, you will see that it is possible to connect more than one sensor to a single input.

Possibilities

The microcontroller that is used in the RCX communicates with the outside world via analogue inputs. The measured quantity is converted into a 10-bit variable. The sensor values are sampled more or less periodically and converted into digital values. These values, which are called RAW inside the microcontroller, range from 0 to 1023. It does not matter which input a sensor is connected to, since the software adapts the sensor input to the type of sensor that is connected.

The RCX has non-polarised, two-wire analogue inputs for measuring external quantities. This approach has both advantages and disadvantages. The fact that the interface is not polarised and uses two wires means that the user can connect the sensor in the manner that suits him best. On the other hand, the entire sensor must be supplied with power via the same

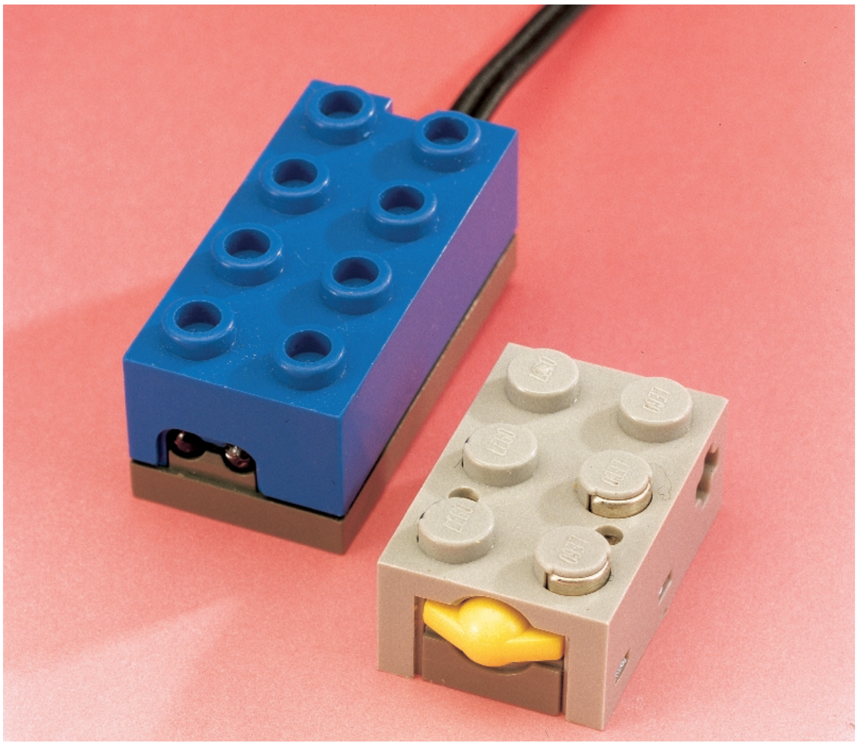

Figure 1. A number of sensors available from Lego for use with the RCX block.

Checking the RAW measurement value

The theory described in this article can be checked using standard software provided by Lego. For this experiment, it is important that the firmware has already been loaded into the RCX.
Start the programming software, select the ‘Program RCX’ option and go to ‘RCX Code’. Activate the test panel in the menu, at the lower right of the screen. Now configure sensor 1 as ‘Touch’ and leave the other two outputs unused.
Next, click on ‘Get Sensor Values’ and check that the value ‘0’ is given for sensor 1. This means that the switch is open. On the RCX module, you must now press the button labelled ‘View’ twice in succession. This selects the second sensor input. The measurement value ‘1023’ will appear on the LCD screen; this is the value of RAW when the switch is open. Since we know that the value of the pull-up resistor is 10 kΩ, we can use a second resistor to make a voltage divider. Connect a 10-kΩ resistor between the two terminals of the sensor input. The value of RAW will drop to 512. With a resistance of 4.7kΩ, the measurement value is 327, and with a short circuit it is 0.

two wires that are also used send measured values back to the RCX. In electrical terms, this means that the analogue inputs are connected to the stabilised 5-V RCX power supply via internal pull-up resistors. A simple measurement shows that the value of the pull-up resistor is 10 kΩ.

In summary, one lead of the sensor is connected to the earth of the RCX, while the other lead is connected to the analogue input of the microcontroller and also to the 5-V supply via a pull-up resistor.

Lego presently supports a number of sensors. The RCX knows what type of sensor is connected from settings in the software. The manner in which the measurement result is handled is the determining factor for the result of the measurement.

Switches — if a switch sensor is connected to an input, the following rules apply: (a) if the value of RAW after a measurement is less than 450, the result is ‘1’ (switch closed); (b) if the value is greater than 565, the value is ‘0’ (switch open).

Light sensor — when a light sensor is used, the RCX produces a measurement value that ranges from 0 to 100. Later on we will see how this value can be controlled. The result of the measurement is equal to (1023 – RAW) ÷ 7.

Temperature sensor — with this type of sensor, the measurement value is converted to degrees Celsius or degrees Fahrenheit. The conversion formula for degrees Celsius is:

temp = (785 – RAW)) ÷ 8

Table 1 shows how the voltage on the analogue input varies as a function of the value of the resistance connected to the input. The value RAW is a direct translation of the input voltage (within the range of 0 to 5 V) to a 10-bit digital value. In the remaining three columns, you can see how the environmental variables (light, temperature and switch open/closed) affect the sensor resistance.

If necessary (for experimental purposes, for example), you can use a potentiometer to emulate a temperature sensor. Configure a 47-kΩ potentiometer as a variable resistor and connect it in series with a 4k7Ω resistor between the two terminals. If the input in question is configured for a temperature sensor, the measurement value will vary between approximately –10 °C and +60 °C when you rotate the shaft of the potentiometer. A certain amount of variation in this range can occur, depending on component tolerances.

If you use the Lego light sensor, it is apparent that the sensor has two externally accessible components. One of these is a red 3-mm LED, while the other is the actual light sensor, which is a phototransistor. A special protocol is used on the input for this sensor in order to cause the LED to illuminate. In this case, the RCX enables a 120-Ω pull-up resistor to the unregulated supply voltage, which is around 8 V. The LED is switched on by a 3-ms pulse, after which the light intensity is read out for 0.1 ms via the phototransistor. The sensor behaves like a light-dependent resistor while the light intensity is being read out. An internal voltage buffer keeps the LED illuminated while the phototransistor is being read out.

Now we know how the RCX works with sensors, how the measured quantities are converted into the measurement value RAW and the quantities that are derived from this value. Unfortunately, you can’t do anything with RAW within the standard Lego software, since the processing of the measurement values takes place inside closed software modules. In a later instalment of this series, we will see that it is however possible to use these quantities with the help of a high-level language, such as Visual BASIC, in combination with the Lego ‘spirit.ocx’ module.

Two sensors on one input

Since each input of the RCX actually only looks for a resistance value, it is possible to

NQC: a different approach

The software developed by Lego that is provided with the kit has a strongly graphical user interface. However, ‘real’ programming fanatics find this too restrictive, and they have developed alternative programming environments. One example of such an alternative system is NQC, which stands for ‘not quite C’. This was developed by Dave Baum and Mark Overmars of the computing science department of the University of Utrecht has written an extensive user’s guide. NQC was developed especially for use with the RCX, and it has a syntax that closely resembles that of C. The NQC environment can be used under Windows 95/98 and NT. It provides a graphical user interface that allows the user to program the RCX block via the TCX Command Center. This programming environment can be downloaded free of charge via the Internet, and it comes complete with an extensive user’s guide. If you are interested, you can find the latest version at http://www.cs.uu.nl/people/markov/lego. You can also find more information about NQC at http://www.enteract.com/~dbaum/lego/nqc.
Even if you do not plan to use NQC, it is very interesting to read the user’s guide. It gives a good insight into how you can use the RCX block in different environments.

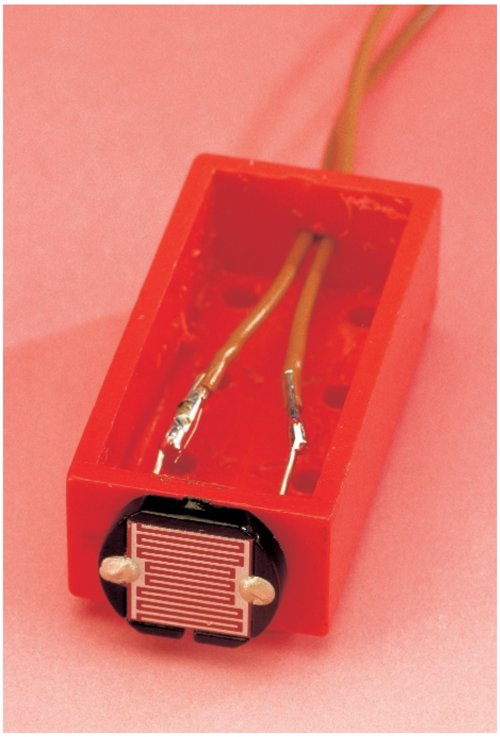

Figure 2. It is not especially difficult to make a real DIY sensor by fitting a standard LDR to a Lego block.

combine sensors. An input that is used for a contact sensor can in principle also be used to read out several contact sensors connected in parallel. When the sensors are arranged this way, they form part of an OR circuit. A prerequisite for this approach is that the response to the closure of a contact sensor is not much more than reversing the current direction of rotation of a motor. After all, if only one sensor input is used, it is not possible to derive any directional information from the sensors.

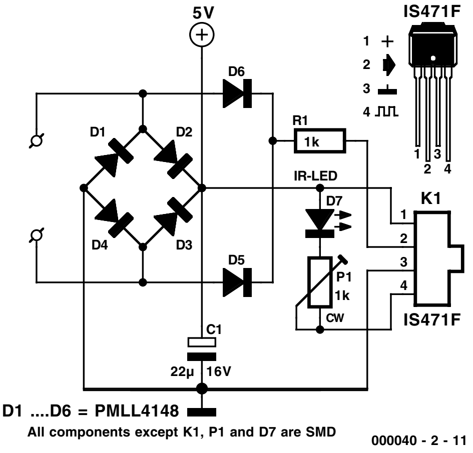

Figure 3. The schematic diagram of the DIY non-contacting object detector.

It is also possible to connect a temperature sensor and a contact sensor to one common set of terminals. The temperature sensor can be read out as long as the contact sensor is not activated. When the contact sensor switch is closed, the temperature sensor is temporarily disabled. As soon as the switch is again open, measuring the temperature can continue as usual.

DIY!

The simplest sensor that you can make yourself is a light sensor using a light-dependent resistor (LDR). If no light shines on the sensor, its resistance is practically infinite. If the sensor is strongly illuminated, its resistance drops to a few ohms. The sensor can easily be made using a standard 2 × 2 or 8 × 2 Lego brick. Drill two small holes in one side (around 1 mm diameter) and pass the leads of the sensor through these holes. Fasten the sensor to the outside of the block using a bit of epoxy glue. On the other side of the block, make a small notch in the bottom edge that is wide enough to fit the cable used to connect motors and sensors. Buy a separate interconnection cable (Lego part number 5041 for 9 cm or 5311 for 25.6 cm) and cut off the connector at one end of the cable (note: if you buy a long cable and cut it in the middle, you will have two new cables, each around 12.5 cm long). Make a knot in the cable 1 cm from the loose end. Then solder the cable ends to the leads of the LDR, and fasten the cable to the inside of the Lego block with a drop of glue. The knot provides an adequate strain relief. The photo in **Figure 2** shows the construction of our prototype.

The LDR reacts to a broader range of the light spectrum than the phototransistor used in the Lego sensor. A phototransistor is normally sensitive in the infrared region. In addition, with the Lego sensor there is a risk of mutual interference, since the light source is located very close to the phototransistor. Although the sensitivity curve of our homemade sensor differs from that of the Lego sensor, it is a perfect and inexpensive alternative. The input to which the LDR is connected should be configured as an input for a Lego light sensor. The measurement value range is from 0 to 100.

Non-contacting object detector

Using the two switches that are provided in the experimenters' kit, a robot can mechanically determine whether there is an obstacle in its path. As soon as an object is touched by the feeler of the contact sensor, the switch closes and the object is sensed.

In the Elektor labs, we have developed a sensor that can detect objects without touching them. **Figure 3** shows the schematic diagram of this small sensor. It is connected to the RCX block via the two connector pins PC1 and PC2. Diodes D1 through D4 rectify the voltage applied to these pins by the RCX block, and C1 buffers the voltage. This DC voltage feeds a Sharp IS417F sensor. This contains a complete modulator/demodulator circuit, and it drives an external infrared LED (D7) via pin 4. As soon as an object appears in front of the sensor, it reflects part of the light that is emitted by the LED. The pulsed infrared light is detected by the sensor and demodulated. The use of modulated light makes the sensor relatively insensitive to interference. If the received signal is strong enough, the sensor output (pin 2) goes low. Resistor R1 is pulled low via diode D5 or D6, and the RCX sees a resistance of around 1 kΩ at the terminals. The distance at which the sensor reacts can be adjusted using trimpot P1. The lower its resistance, the more intense is the light emitted by D7, and thus the greater the distance at which an object is detected.

The main advantage of this solution, in comparison to the Lego light sensor, is that it is much less sensitive to interference from visible light, which is of course always present. The synchronous modulator and detector protect against 'random' responses. There is also a second major difference between the two sensors. Although the Sharp sensor is configured as a light sensor, it gives only the value '100' if an object is in its path or '0' if there is nothing in the way. The Lego light sensor

COMPONENTS LIST

Resistors:
R1 = 1kΩ, SMD
P1 = 1kΩ preset, SMD

Capacitors:
C1 = 22µF/16 V SMD or tantalum

Semiconductors:
D1-D6 = 1N4148 SMD = PMLL4148 (or BAT82)
D7 = IR-LED, 3 mm (wavelength 950 nm), e.g., TSIP4400 (Farnell #178-545) or SFH409 (Conrad Electronics # 183776-33)
IC1 = IS471F (Sharp, Conrad Electronics #185094-33)

Miscellaneous:
Lego-block, type 2x4
Connecting wire + blocks:
Lego-cable, length 26.6 cm (order # 5311)
Lego-cable, length 9 cm (order # 5041)
PCB, order code **000040-1** (see Readers Services page)

provides a continuous range of values between these two extremes.

The circuit board is made to fit exactly in a standard 2 × 4 Lego block. However, the two little posts inside the block must be removed, using a router or a small chisel. In addition, you must drill two small holes in one end of the block to let the sensor and the LED look to the outside. At the other end of the block, make a small opening for the connecting cable.

All diodes, the electrolytic capacitor, the trimpot and the resistor are SMDs. It should also be possible to use normal components, with a bit of cutting and trying. In this case, however, the trimpot will have to be replaced by a fixed resistor (first adjust the distance with a trimpot, then measure its resistance) and you will have to look for an electrolytic capacitor that is small enough to fit into the Lego block (use a small tantalum type). BAT82s make a good substitute for the diodes, if you bend their leads closely around the ends of the packages. Don't forget that there must be enough open space inside the bottom of the block to allow the sensor block to be snapped on top of another block!

The sensor and the LED are mounted on the copper side of the board. This keeps the upper surface of the board nice and flat, so that it can be fully pressed into the Lego block.

The trimpot can be adjusted only after the circuit is fitted into the block. Usually you will find that the sensor right away 'sees itself', so that you will have to make the LED opaque to infrared light on the sides and to the rear. In the prototype, we spread a thick coating of Tippex on the LED, but this proved to be inadequate, probably because the plastic of the Lego block transmits enough light to trigger the sensor. Consequently, the inner surface of the block and even the edge of the hole must also be painted.

Pay careful attention to the position of the sensor when making the sight hole for it in the block. According to the data sheet, the centre of the detector element is located 1.8 mm above the centre of a small recess on the front surface of the sensor. Naturally, the sensor is most sensitive if the opening in the block is located exactly in front of this point.

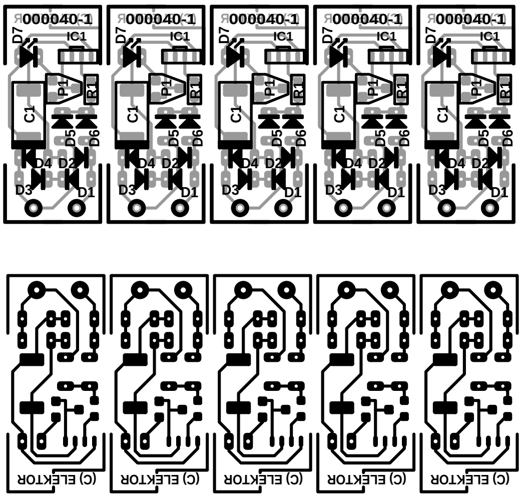

Figure 4. Copper track layout and component layout of the printed circuit board for the object detector.

Figure 4 shows the printed circuit board and component layouts for building this circuit. It is so compact that it can be fitted into a standard 8 × 2 Lego block. Openings for the diode and the sensor must be made on the front side of the block, and an opening for the cable can be made on the other side as already described.

This sensor can be connected to any of the three RCX inputs in place of the existing light sensor. The measurement value switches between 0 and 100, with no intermediate values. If P1 is set to midrange, objects are detected at a distance of around 50 cm. The detector has a viewing angle of approximately 80 degrees.

One final remark: the LED emits a strong infrared light signal. This can disturb the communications between the PC and the RCX when software is being downloaded to the RCX. You should therefore avoid aiming the DIY object detector at the IR sensor of the RCX or the Lego transceiver while software is being downloaded, or else simply disconnect the sensor for the duration.

(000040-2)

Table 1. Analogue input voltage and associated results.

Voltage	RAW	Sensor resistance	Light	Temp (°C)	Contact sensor
0.0	0	0	-	-	1
1.1	225	2k8	-	70	1
1.6	322	4k6	100	58	1
2.2	450	7k8	82	42	1
2.8	565	12k3	65	28	0
3.8	785	32k8	34	0	0
4.6	945	120k	11	–20	0
5.0	1023	∞	0	-	0